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Growing massive black hole pairs in minor mergers of disk galaxies

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Abstract: We perform a suite of high-resolution smoothed particle hydrodynamics simulations to investigate the orbital decay and mass evolution of massive black hole (MBH) pairs down to scales of ~ 30 pc during minor mergers of disk galaxies. Our simulation set includes star formation and accretion onto the MBHs, as well as feedback from both processes. We consider 1:10 merger events starting at $z \sim 3$, with MBH masses in the sensitivity window of the Laser Interferometer Space Antenna, and we follow the coupling between the merger dynamics and the evolution of the MBH mass ratio until the satellite galaxy is tidally disrupted. While the more massive MBH accretes in most cases as if the galaxy were in isolation, the satellite MBH may undergo distinct episodes of enhanced accretion, owing to strong tidal torques acting on its host galaxy and to orbital circularization inside the disk of the primary galaxy. As a consequence, the initial 1:10 mass ratio of the MBHs changes by the time the satellite is disrupted. Depending on the initial fraction of cold gas in the galactic disks and the geometry of the encounter, the mass ratios of the MBH pairs at the time of satellite disruption can stay unchanged or become as large as 1:2. Remarkably, the efficiency of MBH orbital decay correlates with the final mass ratio of the pair itself: MBH pairs that significantly increase their mass ratio are also expected to inspiral more promptly down to nuclear-scale separations. These findings indicate that the mass ratios of MBH pairs in galactic nuclei do not necessarily trace the mass ratios of their merging host galaxies but are determined by the complex interplay between gas accretion and merger dynamics.

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GROWING MASSIVE BLACK HOLE PAIRS IN MINOR MERGERS OF DISK GALAXIES

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ABSTRACT

We perform a suite of high-resolution smoothed particle hydrodynamics simulations to investigate the evolution of massive black hole (MBH) pairs during minor mergers of disk galaxies. Our simulation set includes star formation and accretion onto the MBHs, as well as feedback from both processes. We consider 1:10 merger events occurring around a predicted peak of MBH pair formation at a redshift of $z \sim 3$, in the sensitivity window of the Laser Interferometer Space Antenna. Owing to strong tidal torques acting on its host and orbital circularization inside the disk of the primary galaxy, the companion MBH undergoes distinct episodes of enhanced accretion which cause an increase of the initial 1:10 mass ratio of the MBHs. We also find that the efficiency of MBH pair formation in the nuclei of the remnants correlates with the final mass ratio of the pair itself, so that MBH pairs with larger mass ratios are produced more effectively and promptly. Depending on the initial fraction of cold gas in the galactic disks and the geometry of the encounter, the final mass ratios of the resulting MBH pairs can be as large as 1:2, suggesting that minor galaxy mergers can give rise to MBH pairs with major mass ratios. These findings indicate that the mass ratios of MBH pairs in galactic nuclei do not necessarily trace the mass ratios of their host merging galaxies, but are a consequence of the complex interplay between accretion and merger dynamics.

Subject headings: black hole physics — cosmology: theory — galaxies: mergers — hydrodynamics — methods: numerical

1. INTRODUCTION

The ubiquity of massive black holes (MBHs) at the centers of galactic spheroids (Richstone et al. 1998) together with the “bottom-up” nature of galaxy formation in the currently favored Λ CDM cosmology (e.g., White & Rees 1978) suggest that MBH binaries should form in galactic nuclei during the hierarchical assembly of structure (Begelman et al. 1980; see the recent review by Colpi & Dotti 2009). Such binaries may eventually coalesce via the emission of gravitational waves (Haehnelt 1994), which will be one of the main targets of the next generation of gravitational wave detectors such as the Laser Interferometer Space Antenna (LISA) (Vecchio 2004). Moreover, observations indicate that the masses of MBHs correlate with various properties of their host spheroids, including the luminosity, mass, and velocity dispersion (e.g., Magorrian & al. 1998; Ferrarese & Merritt 2000; Gebhardt & al. 2000). Such relations are suggestive of fundamental physical mechanisms that link SMBH assembly and galaxy formation, and may connect the properties of galaxy mergers with the resulting MBH binaries.

Given all these facts, the study of the dynamics of MBHs during galaxy mergers becomes especially important as a means to connect the cosmological assembly of galaxies with that of MBH pairs and binaries. Many numerical studies have

focused on the effect of galaxy mergers on the growth of MBHs, specifically in relation to their final mass and scaling relations (e.g., Di Matteo et al. 2005; Younger et al. 2008; Johansson et al. 2009). However, much less attention has been devoted to investigating the orbital decay and evolution of MBH pairs *during* mergers, particularly in the unequal-mass regime which comprises the vast majority of such events. Kazantzidis et al. (2005) and Callegari et al. (2009) (hereafter Paper I) showed that the formation of unequal-mass MBH pairs is sensitive to the details of the gasdynamics during the merger process. However, these authors did not follow accretion onto the MBHs, the evolution of their mass ratio and its dependence on the merger dynamics. Such investigations are important, as the mass ratio of MBHs at the time of pairing is a fundamental parameter which drives their subsequent evolution (e.g., Dotti et al. 2007; Lodato et al. 2009).

In this paper, we explore in detail for the first time the formation and mass evolution of MBH pairs using controlled smoothed particle hydrodynamics (SPH) simulations of minor mergers between disk galaxies. The merging systems have a mass ratio of 1 : 10 and our simulation suite includes the effects of star formation and accretion onto the MBHs, as well as feedback from both processes. We model merger events which should produce MBH pairs in the sensitivity window of LISA, around a predicted peak of MBH pair formation with masses $\sim 10^5 M_\odot$ at a redshift of $z \sim 3$.

2. NUMERICAL SIMULATIONS

Our reference galaxy model is a Milky Way type disk galaxy consisting of three components: i) a spherical and isotropic Navarro et al. (1996) dark matter halo with a virial mass and virial velocity of $M_{\text{vir}} = 10^{12} M_\odot$ and $V_{\text{vir}} = 145 \text{ km s}^{-1}$, respectively; ii) an exponential disk of stars and gas with a total mass of $M_d = 0.04 M_{\text{vir}}$, a radial scale-length of $R_d = 4.9 \text{ kpc}$ determined according to Mo et al. (1998), a scale-height of $z_d = 0.1 R_d$, and a mass fraction in gas denoted

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by f_g ; iii) a spherical Hernquist (1990) bulge with a mass and scale radius of $M_b = 0.008M_{\text{vir}}$ and $a_b = 0.2R_d$, respectively. The dark halo was adiabatically contracted to respond to the growth of the disk and bulge (Blumenthal et al. 1986).

We construct a $z = 3$ progenitor of this galaxy model assuming a constant V_{vir} (Li et al. 2007). We follow Mo et al. (1998) and rescale the masses and positions by the ratio of the Hubble constant at $z = 3$ over its present-day value for a Λ CDM concordance cosmology ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$), $H(z=3)/H_0$. The satellite galaxies are constructed with the same relations between structural parameters, and a mass in each component scaled down by $q = 0.1$.

The N -body realizations consist of 10^6 particles in the dark matter halo, and 10^5 particles in the bulge and disk of each model. In addition, each galaxy is initialized with 10^5 gas particles, except in one case (see Table 1 for a summary). We adopted a gravitational softening of 45 pc for both the dark matter and baryonic particles of the larger galaxy, while for the satellite galaxy we used 20 pc. A particle representing the MBH was added at the center of each galaxy with a mass according to the updated $M_{\text{BH}} - M_{\text{bulge}}$ relation of Häring & Rix (2004). Our choice for the galaxy masses in conjunction with the assumption that the MBHs follow the $M_{\text{BH}} - M_{\text{bulge}}$ relation result in MBH masses between $6 \times 10^4 M_\odot$ and $6 \times 10^5 M_\odot$. With these choices, we target the typical masses and cosmic epoch of coalescing MBHs that should be detectable by LISA (Volonteri et al. 2003; Sesana et al. 2005). In addition, we only consider prograde mergers as retrograde encounters are characterised by weak orbital decay and result in a very low pairing efficiency (Paper I). Moreover, we focus on coplanar mergers with the exception of one in which both the orbital plane and satellite disk are inclined by 45° with respect to the disk of the primary (see Table 1). Lastly, we choose merger orbital parameters that are common for merging halos in cosmological simulations (Benson 2005). We refer the reader to Paper I for further details regarding our initialization procedure and chosen parameters.

All simulations were performed with GASOLINE, a multi-stepping, parallel N -body/SPH code (Wadsley et al. 2004). We include atomic cooling for a primordial mixture of hydrogen and helium, and the star formation algorithm is based on the local Schmidt-Kennicutt law (Katz 1992). Feedback from supernovae is treated using the blastwave model described in Stinson et al. (2006). Accretion onto the MBHs is also modelled with a sub-grid recipe (e.g., Springel et al. 2005): the accretion rate \dot{M}_{BH} is estimated from the density ρ_g and sound speed c_s of the gas in its vicinity, and the relative velocity V between the MBH and the gas, via a Bondi-Hoyle-Lyttleton type formula, $\dot{M}_{\text{BH}} = 4\pi G^2 M_{\text{BH}}^2 \rho_g (V^2 + c_s^2)^{-3/2}$ (Bondi 1952). Of this mass-energy input, a fraction $\epsilon_r = 0.1$ is assumed to be radiated away, while a fraction $(1 - \epsilon_r) = 0.9$ is added to the mass of the MBH from its neighboring gas particles. Lastly, a fraction $\epsilon_{\text{fb}} = 0.005$ of the radiated luminosity couples to the surrounding gas as a heating source. This feedback efficiency is tuned so that a number of constraints related to our initial galaxy models can be satisfied (see Section 3.1). In principle, the feedback efficiency depends both on the employed sub-grid model for the interstellar medium and the numerical resolution. For all these reasons, our specific choice differs from those used in a number of earlier studies (e.g., Springel et al. 2005).

3. RESULTS

TABLE 1
SUMMARY OF MERGER SIMULATIONS

f_g primary	f_g satellite	notes
0.3	0.3	reference run
0.3	0.3	inclined ^a
0.3	0.5	1.7×10^5 SPH particles in the satellite ^b
0.1	0.1	-

^a The orbital plane and satellite disk are inclined by 45° with respect to the disk of the primary.

^b This number has been chosen in order to have the same ratio of gas particle mass to MBH mass in both primary and satellite galaxies.

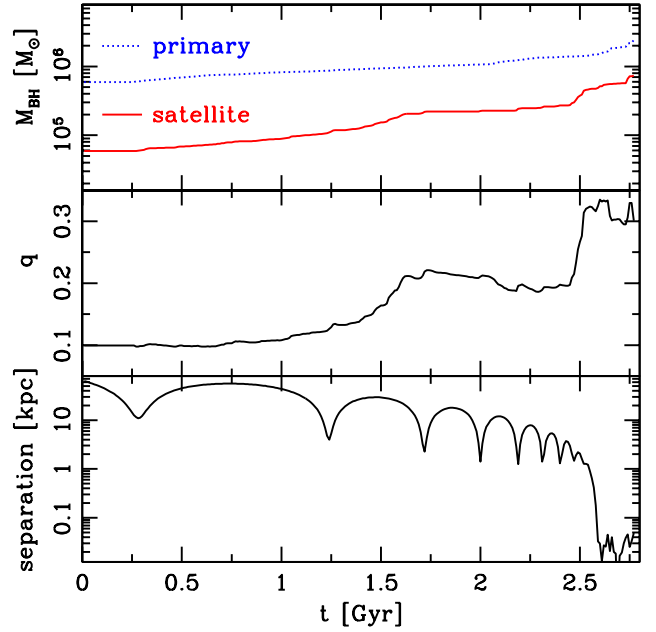


FIG. 1.— Coplanar merger with a disk gas fraction of $f_g = 0.3$ in both galaxies. *Upper panel*: Evolution of the mass of the MBH, M_{BH} , in the primary (dotted line) and satellite galaxy (solid line) as a function of time. *Middle panel*: Evolution of the mass ratio q of the two MBHs as a function of time. *Lower panel*: Orbital decay of the two MBHs as a function of time.

In Section 3.1 we discuss our reference simulation where the gas fraction in both disks of the primary and satellite galaxy is $f_g = 0.3$. Section 3.2 compares this reference case with the other merger simulations performed in this study. A summary of our simulation suite can be found in Table 1.

3.1. Reference Simulation: Coplanar Merger with $f_g = 0.3$

In order to assess the effects of the merger on the mass growth of the MBHs, we first performed simulations of the primary and satellite galaxies evolved *in isolation*. For these tests, we chose the $f_g = 0.3$ galaxy models of our reference simulation. The simulations show that the mass ratio of the two MBHs in the isolated galaxies does not deviate significantly from the initial $q = 0.1$ (the maximum fluctuation around this value is $\sim 10\%$) over a period of more than 2 Gyr. Therefore, we satisfy our working hypothesis that, in equilibrium conditions, the q of the black holes corresponds to the galaxy mass ratio, following from our initial choice of $M_{\text{BH}} - M_{\text{bulge}}$ and galaxy morphology. In addition, these tests provide a measure of the MBH “quiescent” accretion: mass-doubling timescales of the MBHs evolved in isolation are ~ 2 Gyr, i.e. comparable to the typical duration of one of the mergers presented below. This result indicates that any

larger MBH growth or large variation of q during the merger does not stem from secular evolution in the galaxy models or from numerical effects, but rather should be attributed to the galaxy encounter itself.

Figure 1 presents the mass evolution of the two MBHs, the evolution of their mass ratio, and their relative separation as a function of time. By the end of the merger ($t \sim 2.6$ Gyr), owing to dynamical friction, the two MBHs have formed a close pair in the nucleus of the remnant at a separation comparable to the adopted force resolution. This finding confirms our previous results (Paper I) and suggests that gas accretion onto the MBHs and associated feedback is not critical for pair formation in this case. The primary MBH grows quiescently throughout most of the merger, while the secondary one increases its mass tenfold by the time the pair forms. The corresponding increase in the mass ratio of the two MBHs, q , occurs in two distinct episodes, which are elucidated in Figure 2.

The upper panel of Figure 2 shows the evolution of the gas specific angular momentum in the direction of the disk rotation axis, $L_{z, \text{gas}}/M_{\text{gas}}$, as a function of time for both galaxies. For this calculation, we traced back in time gas particles which contribute to the baryonic mass within the central 5 softening lengths of each galaxy right before the third pericentric passage ($t = 1.7$ Gyr). This figure shows that most of the gas in the nuclear region of the satellite at this stage has lost its specific angular momentum on a relatively short timescale. The reason for the angular momentum loss is the strong tidal torques that occur near the second pericentric passage ($t = 1.2$ Gyr) and are induced by the gravitational interaction with the primary galaxy. As a result, a ~ 0.5 Gyr long accretion episode with a corresponding increase of q is observed. As shown in the lower panel of the same Figure, the accretion rate \dot{M} onto the satellite MBH is 10% of the Eddington limit \dot{M}_{Edd} (Eddington 1916) during this phase.

On the other hand, the gas that is funnelled near the center of the primary galaxy has been experiencing a nearly steady loss of specific angular momentum over a very long timescale (Figure 2). This indicates that angular momentum loss in the case of the primary galaxy is not caused by tidal torques arising from the interaction with the satellite, which would occur at pericentric passages and become stronger as the merger progresses. Rather, it is induced by secular evolution (i.e. spiral arms) which redistributes angular momentum throughout the disk. In this context, the effect of initial transient spiral arms is evident during the first ~ 200 Myr. This agrees with the fact that mass growth of the primary MBH is essentially unchanged between the merger and evolution in isolation.

Around the third pericentric passage, ram pressure exerted by the interstellar medium of the primary galaxy strips all the gas from the satellite down to our force resolution. This is in agreement with analytic estimates based on the study by Marcolini et al. (2003); see also Paper I. As a result, the satellite is now devoid of gas (as shown in left panel of Figure 3), and accretion onto the smaller MBH is suddenly halted. A period of slowly decreasing q follows. In fact, during this phase, the more massive MBH continues to accrete gas from its host, experiencing an increase in its Eddington ratio $f_{\text{Edd}} \equiv \dot{M}_{\text{BH}}/\dot{M}_{\text{Edd}}$ as the satellite galaxy is now orbiting close enough to excite gas inflows in the primary disk ($t > 2$ Gyr).

The mass of the satellite MBH sharply increases again (with an associated second increase in q) at kiloparsec-scale separation.

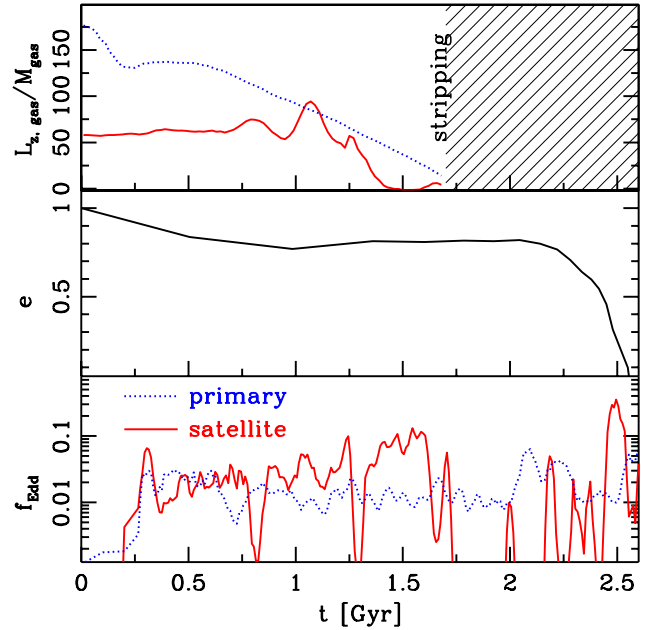


FIG. 2.— Evolution of properties related to the coplanar merger with $f_g = 0.3$ in both galaxies. *Upper panel:* Gas specific angular momentum in the direction of the disk rotation axis in the primary (dotted line) and companion galaxy (solid line) (see text for details). *Middle panel:* Orbital eccentricity of the satellite MBH inside the disk of the primary. *Lower panel:* Eddington ratios, f_{Edd} , of the mass accretion rates onto the primary (dotted line) and secondary MBH (solid line).

rations. At this stage, the secondary MBH orbits inside the gaseous disk of the primary. The mass increase coincides with a sudden drop in the orbital eccentricity of the satellite MBH, as shown in the middle panel of Figure 2. This drop in eccentricity is caused by dynamical friction acting on the satellite along its prograde coplanar orbit in the high-density region of the primary disk. Such orbit circularization is analogous to that found for MBHs in circumnuclear disks (Dotti et al. 2009). Thus, the satellite MBH and its host stellar cusp are moving with a low relative velocity with respect to the disk of the primary. As a consequence, they are able to collect surrounding gas with low angular momentum (in the reference frame of the satellite), creating an overdensity (right panel of Figure 3) from which material is efficiently accreted by the satellite MBH up to a peak $f_{\text{Edd}} \sim 0.3$. On the other hand, accretion onto the primary MBH still relies on angular momentum transport by instabilities in the disk. Such instabilities, triggered by the sinking satellite, are stronger than at earlier times, but still not able to sustain high f_{Edd} .

Overall, by the time the two MBHs form a pair in the nuclear region of the merger remnant, the combination of strong tidal torques and orbital circularization acting on the companion galaxy causes the MBH mass ratio to increase from 1 : 10 to 1 : 3, bringing the pair into a regime of “major” mass ratio.

3.2. The Effect of Gas Fraction and Geometry of the Encounter

Figure 4 compares the evolution of the mass ratio of the MBHs q as a function of time in the coplanar mergers with different disk gas fractions, f_g , and the inclined encounter (see Table 1). We follow the evolution of the interacting systems up to the point where the orbital decay of the satellite galaxy is complete. This figure shows that the first phase of increase in q , caused by dynamical destabilization of the satellite, is evi-

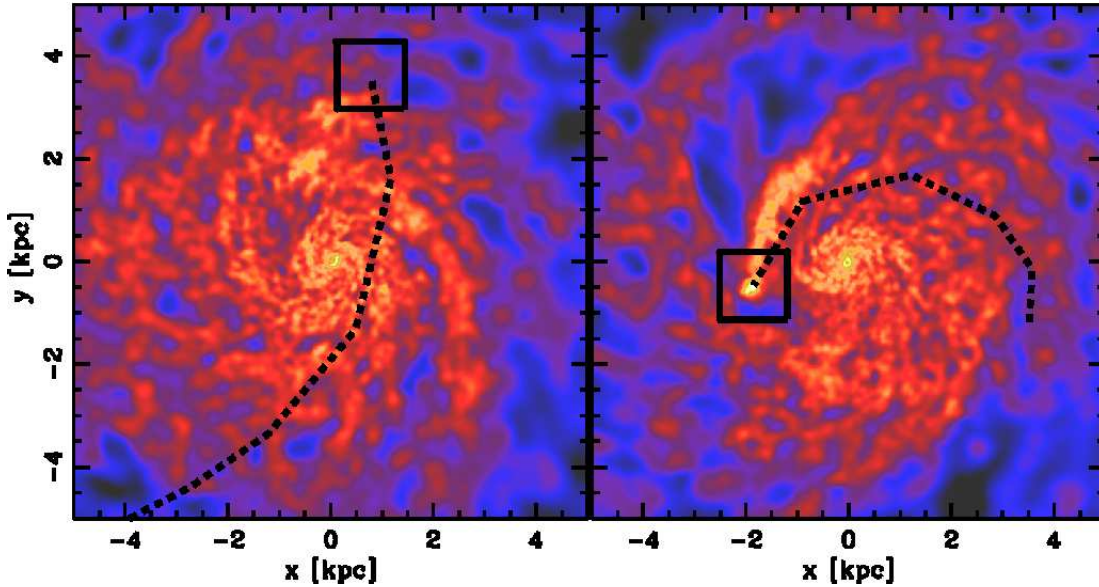


FIG. 3.— Gas density maps at $t = 2.33$ (left panel) and $t = 2.48$ Gyr (right panel), which correspond to just before and after the orbit of the secondary MBH circularizes inside the disk of the primary. The time span between these two snapshots corresponds roughly to two orbits of the satellite. The maps show the inner 5 kpc of the primary. Density is projected onto the x - y plane and is color-coded on a logarithmic scale with brighter colors corresponding to regions of higher gas density. The black dashed line marks the trajectory of the satellite MBH and the square indicates the region around it. The satellite does not appear in the left panel, as ram pressure has stripped its entire gas content. On the contrary, the position of the satellite in the right panel is evidently traced by the overdensity and wake excited in the primary disk.

dent in all cases. Due to the fact that inclination and orbit are fixed in the coplanar mergers, the torques acting on the satellites have the same strength. Interestingly, the highest value of q reached in the first stage traces roughly the amount of gas $\propto f_g$ available for MBH fuelling. In all the mergers considered here, ram pressure is effective in removing gas from the satellite galaxy, once the two galaxy disks come into contact. When this happens, accretion onto the secondary MBH is halted, a result that is independent on the gas fraction and geometry of the encounter.

Figure 4 also demonstrates that the geometry of the encounter is fairly important in determining the relative growth of the MBH pair. Indeed, q is slightly larger in the coplanar merger with $f_g = 0.1$ compared to the inclined encounter with $f_g = 0.3$. Interestingly, the second phase of strong accretion onto the satellite MBH does not always occur. Indeed, it is absent in the merger with the smallest gas fraction ($f_g = 0.1$), and very weak in the inclined $f_g = 0.3$ case. As discussed earlier, mass growth during this phase becomes efficient when the secondary MBH moves inside the gas disk of the primary galaxy and its orbit circularizes. Instead, in the case of $f_g = 0.1$ the satellite does not sink below ~ 400 pc before being tidally disrupted (Paper I). In addition, at these distances the MBH orbit is still mildly eccentric and the background density is not high enough to trigger the second accretion episode.

Similar arguments apply to the inclined $f_g = 0.3$ simulation. Although the orbit of the satellite is eventually dragged down to the plane of the primary disk (Quinn & Goodman 1986), orbital sinking is slow and circularization does not act effectively before tidal shocks disrupt the satellite at ~ 700 pc from the center. For these reasons, the second episode of substantial accretion onto the satellite MBH is precluded in these two cases.

Lastly, we focus on the merger where the initial gas fraction in the primary and companion galaxies is equal to $f_g = 0.3$ and $f_g = 0.5$, respectively. Figure 4 shows that this case is characterized by a much larger final increase in q compared to

our reference case, where the initial gas fraction was equal to $f_g = 0.3$ in both galaxies. Bearing in mind that the only difference between the two initial conditions is the satellite f_g , and that the satellite gas has been entirely stripped by ram pressure at this late stage in both cases, this interesting result can be explained by a combination of two effects. First, a larger initial gas fraction allows the satellite to build a denser stellar core via star formation in response to tidal perturbations during the first two orbits. Consequently, the nuclear region of the satellite harboring the MBH is denser and more massive. It is therefore more efficient at collecting gas from the disk of the primary and it is subject to a slightly enhanced sinking. As a result, the orbit of the secondary MBH undergoes circularization in a denser region of the primary disk, and is able to accrete more gas. Second, by the time the secondary MBH enters the disk of the primary, it is $\sim 60\%$ more massive compared to the case of $f_g = 0.3$. This difference in mass naturally enhances its accretion rate, which scales as $\propto M_{\text{BH}}^2$. By the time a MBH pair forms, their mass ratio becomes 1 : 2.

4. DISCUSSION AND CONCLUSIONS

In this paper, we have demonstrated that *minor* mergers between disk galaxies hosting MBHs can lead to the formation of MBH pairs with *major* mass ratios in the nuclei of merger remnants. The increase in the MBH mass ratios happens in two distinct phases, whose occurrence and relative importance depend on the details of the merger process itself. Specifically, in the initial stages of the encounter, the stronger tidal perturbations experienced by the satellite galaxy, compared to those of the primary, cause an enhanced mass growth of its MBH. In addition, in the last stages of the encounter, the orbit of the secondary MBH may circularize inside the disk of the primary. As a result, its ability to accrete gas and grow in mass relative to that of the primary MBH can be further amplified. Such circularization and associated increase in the accretion rate has been previously reported in small-scale simulations of MBH pairs embedded in a common nuclear disk (Dotti et al. 2009). We note that the amount of gas

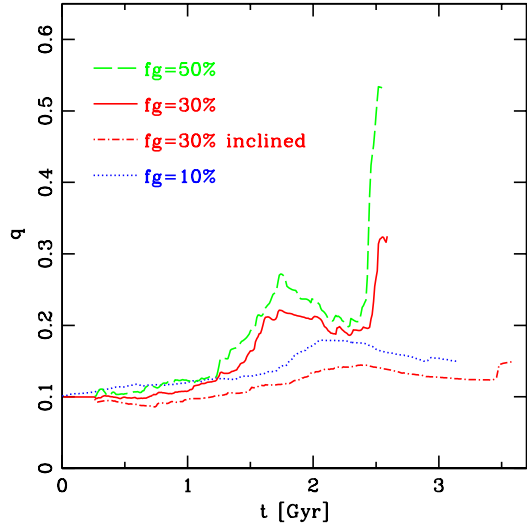


FIG. 4.— Evolution of the mass ratio q of the two MBHs as a function of time in mergers with different gas fractions f_g and orbital inclinations. Dotted and solid lines show results for the coplanar mergers with gas fractions $f_g = 0.1$ and $f_g = 0.3$, respectively, in both galaxies. The dashed line corresponds to a coplanar merger where the initial gas fractions are $f_g = 0.3$ in the primary and $f_g = 0.5$ in the satellite galaxy. The dot-dashed line shows results for the inclined merger with $f_g = 0.3$ in both disks.

left around the MBHs by ram pressure stripping might be underestimated, as the unresolved circumnuclear region could retain some bound gas. In this case, the growth of the secondary MBH may not stop completely at the third pericentric passage, and the final mass ratios may become even larger, strengthening our results.

A cautionary remark concerns the fact that have treated MBH accretion by assuming a Bondi-Hoyle-Lyttleton sub-grid accretion recipe. Indeed, accretion will most likely occur by means of disk angular momentum transport with an effective α -viscosity (e.g., Lin & Pringle 1987). In an attempt to investigate the effect of alternative sub-grid recipes on our results, we applied the recent sub-grid model of DeBuhr et al. (2009) on our simulations. Specifically, we averaged the gas properties inside R_α , which is taken to be equal to twice the gas softening length, and computed the \dot{M}_α of the equivalent α -disk: $\dot{M}_\alpha \sim 3\pi\alpha\Sigma_g c_s^2/\Omega$. Here Σ_g and c_s denote the gas surface density and sound speed, respectively, $\alpha = 0.1$, $\Omega = \sqrt{GM/R_\alpha^3}$, and M is the total mass inside R_α .

These calculations show that the accretion rates onto each of the MBHs are enhanced by roughly the same factor compared to the Bondi prescription. Therefore, adopting this alternative sub-grid recipe does not affect our conclusions concerning the *relative* growth of the two MBHs. While the absolute values of \dot{M}_{BH} can depend on the employed numerical parameters, the physical picture emerging from our simulations should not be substantially affected by the specific choice of sub-grid modelling. Indeed, our findings reflect clear and well-resolved large scale effects, namely how gravitational

torques and orbit circularization make a larger gaseous mass relative to M_{BH} available to the secondary black hole.

The results presented in this paper are especially relevant in the context of MBH gravitational recoils (e.g., Lousto & Zlochower 2009; Tanaka & Haiman 2009). Indeed, if a large fraction of unequal-mass galaxy mergers results in mergers between MBHs with nearly equal masses, then the recoil velocity distribution of the MBH population will be different than expected (e.g., Volonteri et al. 2010). However, the actual recoil velocity distribution will also depend on the magnitude and relative orientation of the spins of the MBHs at the final stage of the merger, which is likely driven by gas dynamics at scales well below those resolved in our simulations (Perego et al. 2009; Dotti et al. 2010).

Our findings together with those of Paper I and of Kazantzidis et al. (2005) suggest that the efficiency of MBH pair formation correlates with the final mass ratio of the pair itself, so that MBH pairs with larger mass ratios are produced more effectively and promptly. Gravitational wave detectors, such as LISA, will enable the use of gravitational wave signals from MBH coalescences as a new, independent probe of cosmic structure formation. Indeed, gravitational waveforms can allow the determination of mass, spin, and orbital parameters of the merging MBHs (Vecchio 2004). In principle, this information could be used to infer the masses of the merging host galaxies. However, our results demonstrate that this connection cannot be made by simply applying the observed scaling relations between the masses of MBHs and the properties of their host galaxies, even if these scalings are applicable to galaxies throughout cosmic history. The findings presented here suggest that the mapping between galaxy and MBH mergers depends on various factors, such as the gas content of the merging galaxies and the encounter geometry, and as such might need to be approached in a probabilistic way. Such investigations would require a combination of a series of merger experiments that explore a larger parameter space with semi-analytical models of the co-evolution between galaxies and MBHs.

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